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Chandra Observations of Nearby Spiral Galaxies

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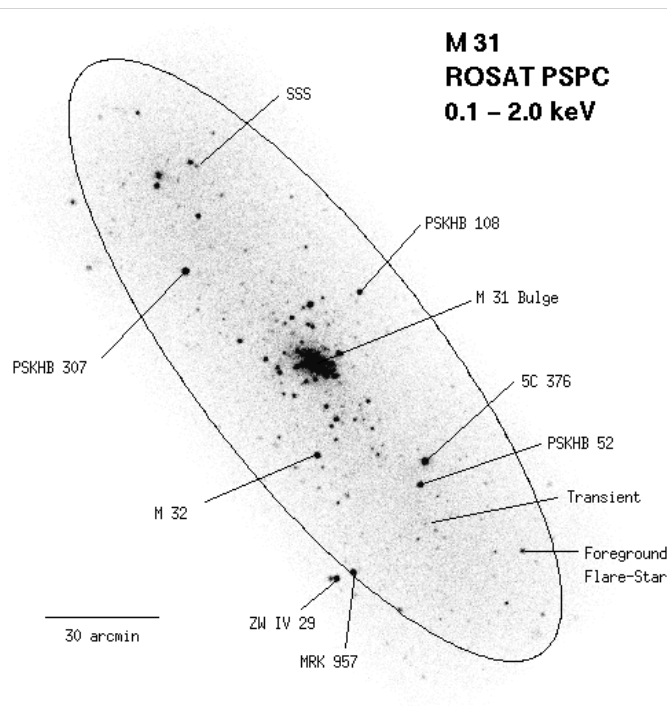
Abstract. Chandra is revolutionising our understanding of the X-ray emission from spiral galaxies. Before Chandra, detailed extragalactic studies were limited to Local Group galaxies. We are now able to obtain detailed inventories of sources in galaxies outside the Local Group, allowing population studies for the first time. In this review I will first discuss some intriguing observations of globular cluster sources in M31, then move outside the Local Group and summarise the observational properties of sources in several spiral galaxies (both bulge dominated and disk dominated). The X-ray colors and variability characteristics suggest that most of these sources are accreting binaries. High mass X-ray binaries are formed preferentially in disk galaxies. Finally, I show that the luminosity functions of spiral galaxies can be qualitatively understood in terms of simple population models.

1. Introduction

This article focuses on how Chandra's superb angular resolution has improved our understanding of the X-ray emission from spiral galaxies, especially the discrete source population. I would therefore like to start by briefly reviewing the pre-Chandra view of spiral galaxies, and explain why Chandra is so crucial for population studies. The pre-Chandra view of Local Group galaxies was quite detailed. This is demonstrated in Figure 1, which shows the PSPC image of the Local Group spiral M31 (see Supper et al 2001). A total of 560 sources are detected in a 10.7 deg^2 field of view down to a limiting sensitivity of $10^{35}\text{-}10^{36} \text{ ergs s}^{-1}$. The bulge region is very confused, and contains many unresolved sources and diffuse emission. There are also bright sources associated with the spiral arms. Many of the detected X-ray sources have optical counterparts, including 55 stars, 33 globular clusters, 16 supernova remnants and 10 background sources.

Outside of the Local Group, however, the resolution of pre-Chandra telescopes limited detection to all but the brightest discrete sources, and confusion was always a problem. The poor resolution also results in large positional uncertainties, making optical identifications difficult (see Section 3.). The improvement in resolution with the advent of Chandra is illustrated by comparing the ROSAT HRI observation of M101 (Wang et al 1999) with the recent Chandra paper on the same galaxy by Pence et al 2001 (e.g. see the Figure 2.) Wang et al (1999) detected a total of 51 sources in the HRI field of view (30 arcmin),

Figure 1. PSPC image of Local Group galaxy M31 from Supper et al 2001.



whereas Pence et al 2001 detected 110 sources on the S3 chip alone (field of view 8 arcmin).

Chandra is an excellent instrument for nearby galaxies. It's excellent angular resolution reduces confusion and also results in lower background leading to better detection sensitivity. It allows us to obtain detailed inventories of X-ray sources in galaxies beyond the Local Group for the first time. We are able to classify X-ray sources as binaries, supernova remnants and HII regions by examining their X-ray properties and looking for optical/radio counterparts. Extending high resolution X-ray studies to galaxies beyond the Local Group allows us to determine how properties of X-ray sources change with star formation rate and star formation history. This in turn will lead to improved theoretical understanding of how X-ray sources form and evolve.

2. Bright Globular Cluster X-ray Sources in M31

Approximately 900 arcmin² of M31 was surveyed by Chandra in AO2, mostly by the HRC GTO team (PI Steve Murray) and Rosanne Di Stefano. One of the most interesting results to emerge from this census is that the most luminous X-ray sources in the survey are associated with globular clusters. This analysis has been carried out by Rosanne Di Stefano and her colleagues (see Di Stefano et al 2001). Of the 30 known globular clusters in the survey fields, 17 are new. One third of these globular cluster X-ray sources have luminosities $L_x > 10^{37}$ erg

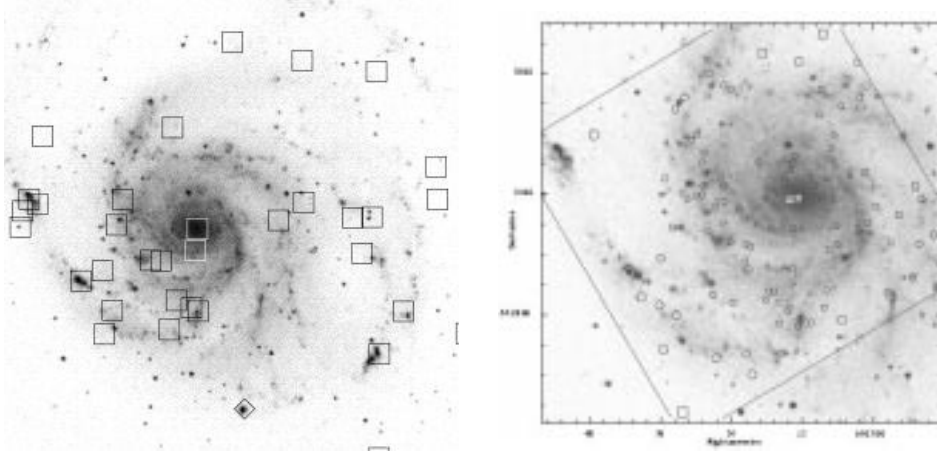


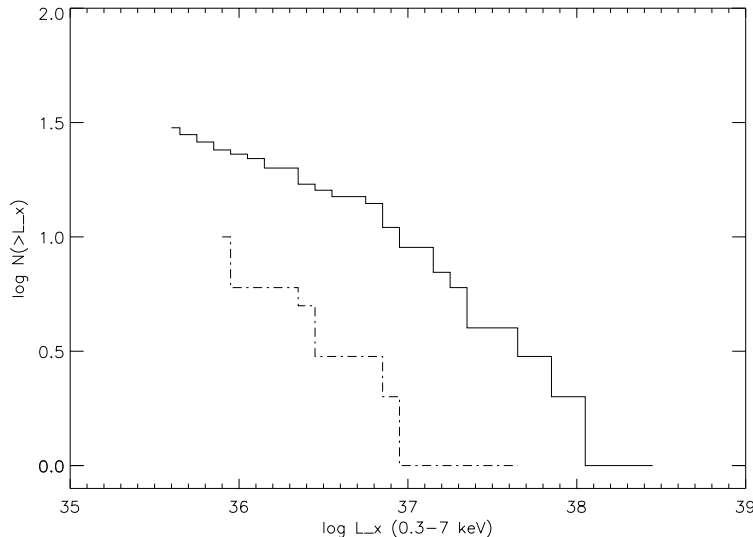
Figure 2. Left panel: ROSAT HRI detected sources marked on an optical image of M101 (Wang et al 1999). Right Panel: Chandra sources in the same area (Pence et al 2001).

s^{-1} . This is in contrast to Milky Way globular clusters where only about 10% have X-ray luminosities $L_x > 10^{37} \text{ erg s}^{-1}$. The brightest of the M31 globular cluster sources in the Chandra survey is Bo 375, which has an X-ray luminosity $L_x \sim 2\text{--}6 \times 10^{38} \text{ erg s}^{-1}$, and a 16 hour period (probably orbital). The luminosity of this source is a magnitude larger than the brightest galactic globular cluster X-ray source, and larger than the Eddington Limit for a $1.4 M_\odot$ neutron star.

The fact that M31 has more luminous globular cluster X-ray sources than the Milky Way has long been established (e.g. Primi et al 1993, and the discussion by Di Stefano et al 2001) and is illustrated in Figure 3, which shows the cumulative luminosity functions for the Milky Way and M31. However, the reason for the difference has been controversial. One possibility is simply that M31 has more globular clusters than the Milky Way (the population could be 20 times larger) and hence the probability of finding high luminosity sources is greater. It is also possible that there really is an excess of high luminosity X-ray sources in M31 globular clusters compared to Milky Way clusters. Several possibilities are considered for the origin of the brightest sources by DiStefano and her collaborators, including that the sources may be composites, beamed, that M31 clusters have lower metallicity than Milky Way globular clusters, or that they contain accreting black holes.

One especially interesting suggestion is that the brightest sources are examples of thermal-timescale mass transfer onto a neutron star. This will occur when the donor star expands to fill its Roche lobe, leading to transfer onto the compact object via the L1 point. The transfer rate will be very rapid, resulting in super-Eddington luminosities. Thermal-timescale mass transfer from a high mass donor star onto a black hole (with modest beaming) has been suggested as a possible mechanism for producing the very high ($L_x > 10^{39} \text{ erg s}^{-1}$) luminosities seen in so-called “ultra-luminous” sources in starburst galaxies (King et al 2001). DiStefano et al find that they can explain the 16-hour period of Bo 375 and its high luminosity with an episode of thermal-timescale mass transfer

Figure 3. Cumulative luminosity functions for the globular cluster X-ray sources in M31 observed with Chandra (solid line) and the Milky Way (from Verbunt et al 1995)



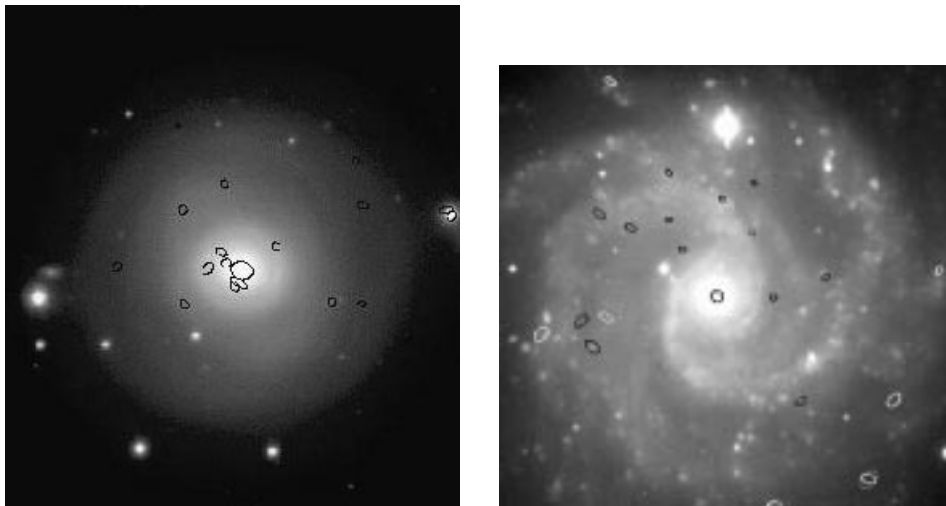
from a donor star in the range $1.1\text{--}1.6M_{\odot}$. This value is extremely interesting, and may hold the clue to explaining at least some of the differences between the X-ray sources in Milky Way and M31 globular clusters. It is very unlikely that Milky Way globulars contain many potential donor stars of this mass, since stars with masses $\geq 0.8M_{\odot}$ have evolved off the main sequence. The globular clusters in M31 may be younger, in which case they would have many more higher mass donor stars available.

3. Hypernova Remnants in M101?

One of the most intriguing suggestions to emerge from ROSAT observations of M101 is that 5 known optical supernova remnants have very high X-ray luminosities ($L_x = 10^{38}\text{--}10^{39}$ ergs s^{-1}). Wang et al (1999) suggested that these highly luminous might be the remnants of “hypernovae” - the energetic event (e.g. massive star callapsing) responsible for gamma ray bursts.

Three of these remnants have been observed by Chandra, as reported by Snowden et al. One of the X-ray sources is highly variable and therefore unlikely to be a supernova remnant. One of the sources was found (with Chandra’s improved spatial resolution) not to be associated with the optical remnant. The last X-ray source was resolved into 2 sources, one of which is coincident with the optical remnant, but has a “normal” X-ray luminosity. The second source is a bright nearby binary.

Figure 4. Greyscale optical images of the SO galaxy NGC 2681 (left) and the the late spiral NGC 3184 (right) with detected X-ray sources.



4. Observational Properties of X-ray Sources

4.1. Optical/X-ray Comparisons

Chandra observations of nearby spiral galaxies are revealing patterns similar to that observed by ROSAT for Local Group galaxies. Sources can be divided broadly into “bulge” and “disk” components. Bulge sources typically cluster around a central nuclear source (which may be resolved and is often extended) and disk sources trace the spiral arms. This pattern is illustrated in Figure 4, which shows detected X-ray sources plotted on an optical image of NGC 2681 (mostly bulge) and NGC 3184 (mostly disk). Similar patterns have been observed for M101 (Pence et al 2001) who find that essentially all the sources lie along the spiral arms; interarm sources are consistent with background AGN. Tennant et al 2001 find that 7/10 of the brightest sources in M81 fall in the disk spiral arms. The bulge sources in M81 follow the I-band profile. Kaaret (2001) detected 6 sources in M100, all of which lie in the spiral arms. Blanton et al (2001) show that the SO galaxy NGC 1553 follows the classic “bulge” pattern.

4.2. Variability

Many Chandra sources in nearby galaxies show evidence for variability, as might be expected from previous Einstein/ROSAT observations. Multiple Chandra observations of NGC 3184 and NGC 2681 reveal that approximately 40% of the sources are variable on scales of 1-4 months. In M100 4/6 sources detected by Kaaret (2001) and one source in Circinus (Bauer et al 2001) show variability compared to archival data from other missions. Short term variability (i.e. within a Chandra observation) has also been observed. In Circinus 4 sources exhibit short term variability, 5 in NGC 1553 and one (very soft) source in M81 (Tennant et al 2001).

4.3. Spectra

Figure 5 shows the X-ray color-color diagram for sources in NGC 1291, NGC 2681, NGC 3184 and NGC 5236. All of these galaxies are face-on, thus minimising the effects of extinction. NGC 1291 and NGC 2681 are bulge dominated systems whose sources are plotted as triangles. NGC 3184 and NGC 5236 are disk galaxies and are plotted as filled circles. The Chandra bandpass has been split into three bands: soft (0.3-1.0 keV), medium (1.0-2.0) and hard (2.0-8.0). The hard color is defined as $(hard - medium)/total$ and the soft color as $(medium - soft)/total$. The spectrum of a source becomes harder as it moves to the right and up in this diagram.

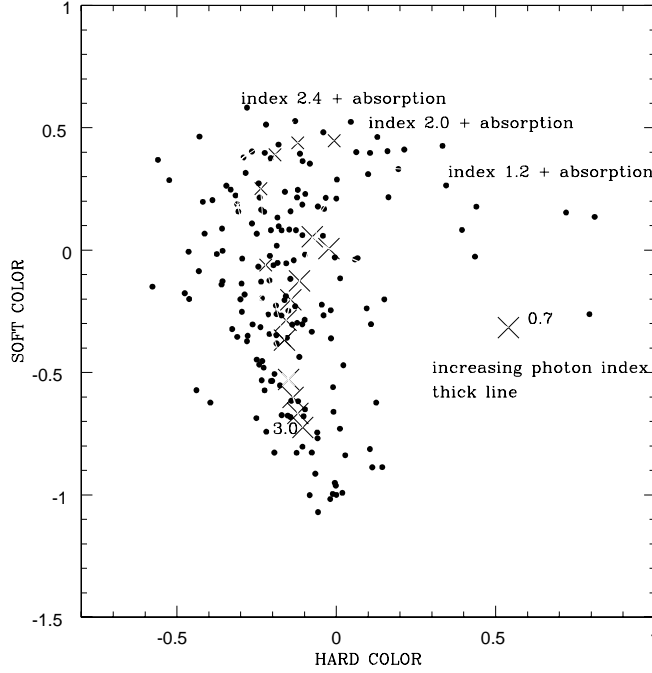
Also plotted in Figure 5 are the predicted colors of power-law spectra with increasing photon index (thick solid line). The tick marks on the thick line mark increasing values (in steps of 0.2) of the photon index. The lowest value photon index (hardest) plotted is 0.7 and the highest value (softest) is 3.0. Finally, the effect of adding absorption to a simple power law is illustrated with the thin solid lines (minimum added absorption is $N_H = 10^{21} \text{ cm}^{-2}$ and maximum is $N_H = 10^{22} \text{ cm}^{-2}$). It is clear from this diagram that most of the sources, whether from bulge or disk dominated systems have colors that are consistent with power law spectra plus absorption. This is further illustrated in Figure 6, which shows colors for sources in M82 (diamonds) and NGC 3184 (crosses). The X-ray sources in M82 have colors which are consistent with higher extinction, as might be expected for an edge-on galaxy compared to a face-on spiral (NGC 3184). There is a population of sources (mostly in the disk galaxies) that have spectra which are very soft (soft color < -0.5). It is not clear whether these soft sources are not found in bulge systems, or whether the detection limit for soft sources is higher in bulges because of a higher background of diffuse emission.

These broad conclusions - that the spectra of most sources in spiral galaxies are consistent with a powerlaw spectrum plus absorption and that there is a population of soft sources - are supported by work by other groups. Bauer et al and Pence et al (2001) find that a powerlaw plus absorption is a good description for sources in Circinus and M101 respectively. Tennant et al (2001) find that sources in M81 are described by a $\gamma=1.6$ powerlaw spectrum with galactic column. Finally a population of soft sources is observed in M81 (Tennant et al) and M101 (Pence et al). Blanton et al do not observe soft sources in NGC 1553, but the limiting flux is rather high ($10^{38} \text{ erg s}^{-1}$).

4.4. Observational Summary

The observations described in this section suggest that the discrete source population in spiral galaxies is dominated by binaries. This interpretation is consistent with the colors and variability characteristics of the sources. In disk galaxies the sources follow the spiral arms; these may be short-lived high mass X-ray binaries in star forming regions. It is tempting to suggest that the low-luminosity soft sources found in so many systems may be supernova remnants. However, at least some of these sources must be accretion powered because they are variable.

Figure 5. X-ray color-color diagram for two bulge dominated galaxies and two disk dominated galaxies. See text for details.



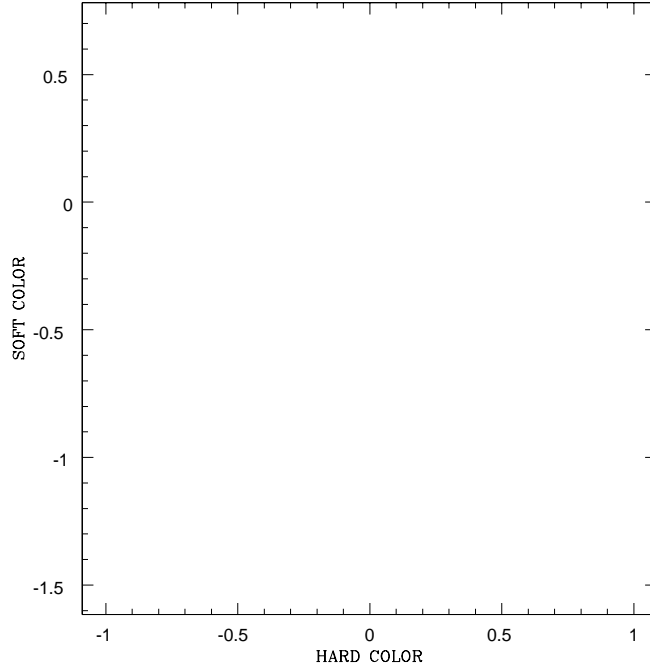
5. X-ray Luminosity Functions

The traditional way to compare X-ray source populations in different galaxies is to look for differences in the cumulative luminosity function. This is the number of sources with a luminosity greater than a given luminosity (L) plotted against L . The luminosity function for two spiral galaxies, NGC 3184 and IC 5332, is shown in Figure 7. The line is the best fit single power-law to the NGC 3184 data. Galaxies with luminosity functions with flat slopes have a relatively large number of high luminosity sources.

Slopes have been measured for the luminosity functions for several galaxies. These are summarised in Table 1. Included in this table are the disks of four classic spirals (M81, M101, IC 5332 and NGC 5236), one starburst (NGC 4038) and three early type/bulge systems (NGC 1553, the bulge of M31, and NGC 4697). The M31 luminosity function from Shirey et al uses XMM data. Two of the early-type systems have breaks in the luminosity functions (NGC 1553 at 4×10^{38} ergs s $^{-1}$ and NGC 4697 at 3.4×10^{38} ergs s $^{-1}$.)

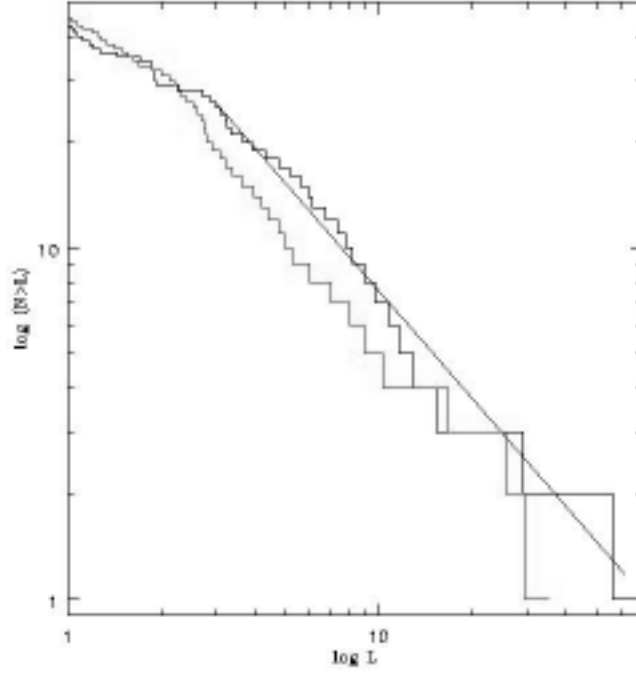
The most striking thing about these results is that the disks and star forming galaxies seem to have systematically flatter slopes than the bulges. A possible caveat is that the detection limit for NGC 1553 is 2×10^{38} erg s $^{-1}$, so that the luminosity range for this galaxy does not overlap very well the other galaxies discussed here. If this observation is correct, however, it implies that the disks have a larger fraction of higher luminosity sources relative to the total than do early type systems. This can be most naturally explained if systems with on-going

Figure 6. X-ray color-color diagram for an edge-on starburst galaxy (M82) and a face-on disk galaxy (N3184).



Galaxy	LF slope	ref
Disks/star forming galaxies		
M81	0.5	Tennant et al
M101	0.8	Pence et al
IC 5332	1.1	this work
NGC 5236	0.64	this work
NGC 4038	0.45	Fabbiano et al
Bulges		
NGC 1553	1.7	Blanton et al
M31	1.79	Shirey et al 2001
NGC 4697	1.76	Srazin et al 2000

Figure 7. Luminosity functions for two spiral galaxies, NGC 3184 and IC 5332

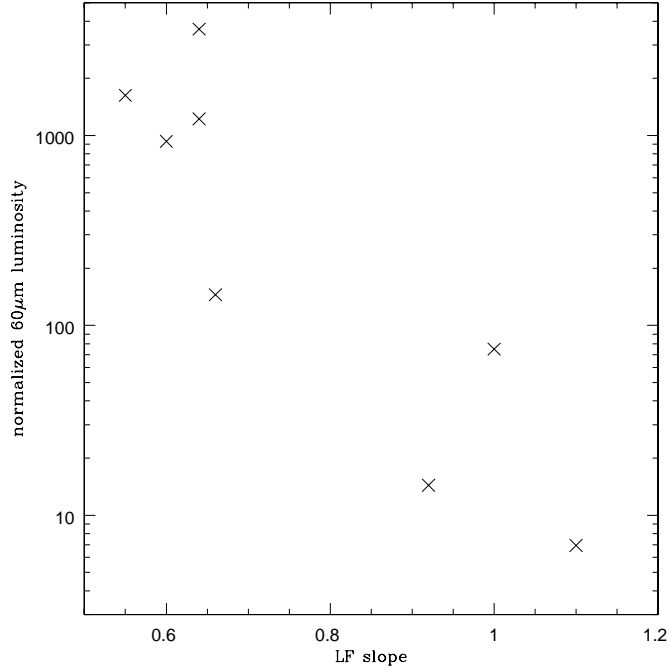


high mass star formation have a population of high mass X-ray binaries that dominate the high end of the luminosity function. This hypothesis is supported by the plot in Figure 8, which shows the slopes of the luminosity functions of several spirals plotted against the integrated $60\mu\text{m}$ luminosity. There is a clear correlation between the $60\mu\text{m}$ luminosity (a measure of the star formation rate) and the slope of the X-ray luminosity function, in the sense that flatter slopes have higher star formation rates.

6. Simple Population Models

The luminosity functions described above can be qualitatively understood in terms of simple binary population models. As an example, consider the models of Wu (2001). He describes binary formation from three populations: an impulsive starburst event, constant binary formation, and primordial binary formation. Primordial binary formation occurs at a low rate throughout the lifetime of the galaxy as low-mass stars in binary systems evolve and their orbits decay, initiating mass transfer. These systems tend to be low luminosity ($L_x \sim 10^{36} \text{ erg s}^{-1}$) and so do not contribute significantly to the sources detected by Chandra in nearby galaxies. An impulsive star formation event will generate many binary systems with about the same age; initially many of these will be high mass binaries. This binary population will evolve with the most luminous systems

Figure 8. The slope of the X-ray luminosity function plotted against the $60\mu\text{m}$ luminosity

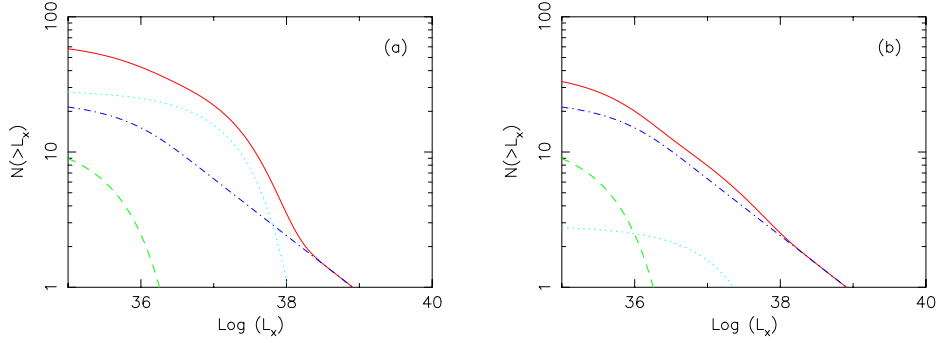


dying first. Finally, in many galaxies (e.g. disk galaxies with star formation occurring in the spiral arms) binaries will be forming continuously.

Figure 9 shows a simulated luminosity function from Wu 2001. The overall normalization is set to the luminosity of M81. The solid line shows the “observed” luminosity function. The dotted line shows a binary population formed in a starburst event, the dashed line shows binaries that are continually forming. In the left panel the most luminous binaries formed in the starburst episode have already turned off; the systems that are forming now dominate the high end of the luminosity function. In the right panel the starburst population is relatively unimportant and the “constant star formation” population dominated the luminosity function.

These models can be extended to other galaxies. The luminosity functions in young starbursts like the Antennae (NGC 4038) will reflect the birth luminosity function, and will show little or no aging. Continually forming binaries will dominate the luminosity functions in disk galaxies. If bulges and elliptical galaxies are formed via mergers and starbursts then (as suggested by Wu 2001) we might expect to see “breaks” in the luminosity function corresponding to the last major star formation event. Breaks in the luminosity functions have been observed in early type systems, as described in Section 5.. These breaks may be due to past starburst episodes, or they may be due to the transition from neutron star binaries to black hole binaries. Much more work is necessary to determine whether the break at $4 \times 10^{38} \text{ ergs s}^{-1}$ is universal, and whether breaks are seen at other luminosities.

Figure 9.



7. Summary and Conclusions

Chandra’s view of nearby spiral galaxies is spectacular, revealing a multitude of X-ray sources. In our neighbor M31 Chandra has detected several (surprisingly) bright X-ray sources associated with globular clusters, the brightest of which (Bo 375) has an X-ray luminosity $L_x \sim 2\text{--}6 \times 10^{38} \text{ erg s}^{-1}$. Bo 375 (and possibly other sources) may be experiencing an episode of thermal timescale mass transfer, which will allow persistently super-Eddington luminosities.

Chandra provides detailed X-ray images of galaxies beyond the Local Group for the first time. For example, the unprecedented positional accuracy of Chandra allowed Snowden et al (2001) to show that several sources in M101 cannot be hypernova remnants, as previously suggested from ROSAT data. Chandra imaging of several nearby spirals shows that the X-ray source population is dominated by accreting binaries. Bright sources are frequently seen along the spiral arms, suggesting that these sources are mostly HMXBs. This conclusion is supported by a correlation between the slope of the X-ray luminosity function and the $60\mu\text{m}$ luminosity.

The luminosity functions of these galaxies can be qualitatively understood in terms of simple population models. In disk galaxies binaries are forming continually, whereas in bulges a “decaying starburst” component may be important. The very flat luminosity functions in starbursts may reflect the birth luminosity distribution. There is evidence for breaks in the luminosity functions of early-type systems. These may be due to past starburst episodes, or possibly the transition from neutron stars to black hole binaries.

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